Lagrangian perspectives of deep water export from the subpolar North Atlantic

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[1] Direct observations at the Grand Banks have raised a quandary concerning the pathways of the lower branch of the meridional overturning circulation: In contrast to moored current meters that depict an intense, narrow Deep Western Boundary Current (DWBC), observations using different float types failed to show this continuous export path. Here, this issue is addressed by a Lagrangian analysis of synthetic particles in an eddy-resolving circulation model. Due to intense eddy activity around the Grand Banks, about 40% of the deep water in the DWBC is diverted into the interior, spreading southward along the western flank of the Mid-Atlantic Ridge or with the eddying flow field in the basin interior. Imposing constraints on the vertical displacements of particles similar to those experienced by observational floats further reduces their adherence to the DWBC, particularly near the southern tip of the Grand Banks. **Citation:** Getzlaff, K., C. W. Böning, and J. Dengg (2006), Lagrangian perspectives of deep water export from the subpolar North Atlantic, *Geophys. Res. Lett.*, *33*, L21S08, doi:10.1029/2006GL026470.

1. Introduction

[2] The area of the western Newfoundland Basin south of Flemish Cap constitutes a key region for the water mass exchange between the North Atlantic's subpolar and subtropical gyre. For this reason, it has become a focus of interest especially with regard to its potential for a detection of variations in the deep branch of the MOC. However, while further south in the subtropical western North Atlantic there is ample evidence from large-scale hydrographic and tracer measurements that North Atlantic Deep Water (NADW) is transported south by a continuous Deep Western Boundary Current (DWBC) [*Smethie*, 1993; *Molinari et al.*, 1998; *Smethie et al.*, 2000], the pathways through the Newfoundland Basin are still controversial. Repeated multi-year observational programs using moored current meters off the southern tip of the Grand Banks depict a southward transport of NADW by a mean DWBC of about 12 Sv [*Clarke et al.*, 1998; *Fischer et al.*, 2004 (hereafter: F04); *Schott et al.*, 2004 (hereafter: S04); *Schott et al.*, 2006]. How much of this represents a continuous western boundary pathway to the subtropics remains unclear, however, due to the interaction with an adjacent, even stronger northward flow of dense water with the deep-reaching North Atlantic Current (NAC); integrated across the western portion of the Newfoundland Basin this even gives a net *northward* deep-water transport [S04]. Of particular concern has been the behavior of floats launched in the DWBC as part of several programs aiming to elucidate the export pathways of NADW: almost none of the profiling floats used by *Lavender et al.* [2000] and *Fischer and Schott* [2002], or the isobaric floats used in a more-recent program (A. Bower, personal communication, 2006) have exhibited a continuous pathway around the tip of the Grand Banks; nearly all of them were instead diverted from the DWBC onto irregular paths through the interior Newfoundland Basin. The notion of an interior pathway appears qualitatively supported by analyses of hydrographic data [*Lozier*, 1997] and passive tracers such as CFCs [*Rhein et al.*, 2002; *Kieke et al.*, 2006].

[3] An important aspect of the deep flow field off the Grand Banks as revealed by the current meter measurements, is its strong variability on time scales of weeks to months. The time series reported by S04 exhibit DWBC transport changes between more than 30 Sv to the south and phases of almost vanishing or even northward transport. The main cause of this variability is the eddy activity associated with the intense, very-deep reaching NAC. Understanding of the export pathways in this region therefore requires a determination of the effects of the DWBC encounter with this NAC-related eddy variability. To aid in the interpretation of observational data, we investigate the pathways of deep water using Lagrangian analysis of synthetic particles in an eddy-resolving model. In addition, different properties of quasi-Lagrangian floats are simulated, demonstrating the potential drawbacks of using conventional float designs in this region.

2. Model and Lagrangian Diagnostics

[4] Results presented here were computed with an eddy-resolving primitive equation model of the North Atlantic (extending from 18°S to 70°N), based on the Geophysical Fluid Dynamics Laboratory's MOM2.1 code [*Pacanowski*, 1996]. As part of the FLAME hierarchy of models [*Dengg et al.*, 1999], several refinements were applied to the configuration [e.g., *Eden and Böning*, 2002]. The most relevant to this study are: a Mercator grid with a longitudinal resolution of 1/12°, i.e., about 6 km in the region of the Grand Banks, and 45 z-coordinate levels in the vertical. Lateral subgrid-scale eddy viscosity is parameterized by biharmonic mixing (2×10^{10} $m^4 s^{-1}$). Atmospheric forcing is prescribed from a monthly climatology of ECMWF-based fluxes [*Willebrand et al.*, 2001]. For the analysis shown here, year 9 of a spinup from rest and climatological data is used.

[5] The Lagrangian analysis of the model output used synthetic floats integrated over 15 years (by repeatedly cycling through that one year of data), including a time-step

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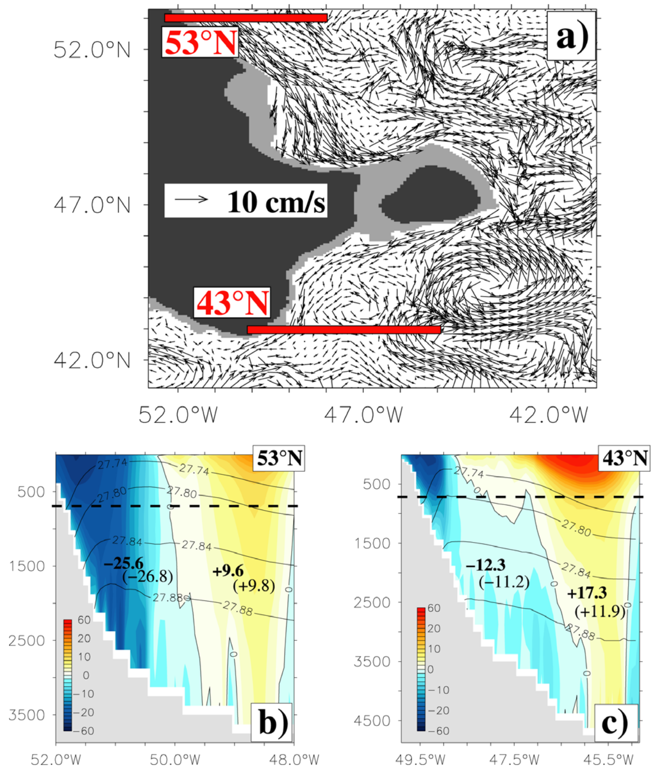

Figure 1. (a) Averaged velocity field of model year 9 at 1500 m (every 3rd vector shown) with the starting positions of the different float computations; shading denotes 1500 m topography (light grey) and shelf (grey). (b and c) Mean meridional velocity sections (cm/s) at 53°N and 43°N with σ_Θ contour lines. Numbers denote vertically integrated transports below 700 m (bold numbers) and for water denser than 27.80 kg/m^3 (thin).

scheme adapted to the local velocity field [cf. *Kröger*, 2001], with time-steps on the order of up to an hour. The computation of Lagrangian volume transports used a method described by *Blanke and Raynaud* [1997], which divides a given transport into Lagrangian volume "packages". All analyses shown here concentrate on those floats that eventually arrive in the DWBC at 32°N.

3. Time-Mean Circulation

[6] The model's annual mean Eulerian velocity field at 1500 m depth (Figure 1a) shows an intense DWBC with realistic maximum speeds and width that extends from the Labrador Sea all the way to the southern tip of the Grand Banks. The 1/12° model captures the salient features of the observed DWBC structure and transports (Figures 1b and 1c) obtained from current-meter sections at 53°N and 43°N [F04; S04], depicting a DWBC with mean transports of 25.6 Sv below 700 m at 53°N (25.4 Sv in F04) and 12.3 Sv at 43°N (13.2 Sv in S04).

[7] In the latter section, a deep reaching branch of the NAC can be identified with a deep northward transport of 17.3 Sv. However, in the annual mean field shown in Figure 1a), intense mesoscale eddy features still dominate the circulation near the shelf break, indicating that eddy activity should have a substantial impact on the deep export pathways. This intense eddy variability is also documented in the current meter data of *Clarke et al.* [1998] and S04 (their Table 2), with eddy kinetic energies (EKE) at 43°N and 1500 m depth exceeding 100 cm^{2}s^{-2} in the DWBC/NAC-transition regime. The model replicates the observed variability pattern at this section, with EKE values somewhat lower than observed (up to 90 cm^{2}s^{-2}).

[8] The Eulerian view alone cannot depict the fate of individual parcels of DWBC water near the tip of the Grand Banks. A first impression of export paths through the Newfoundland Basin is obtained by performing a float computation using an annual mean of the full 3-dimensional velocity field with 6500 Lagrangian floats seeded across the DWBC at 53°N from 700 m depth to the bottom. Figure 2 displays the trajectories of all floats that are exported south in the DWBC across 32°N. An interesting aspect is that even with the time-mean field only 16% of the water volume tagged at 53°N reaches the boundary regime at 32°N. The major part (68%) of the water remains in the subpolar gyre. (The study area in these experiments was restricted to the region shown in Figure 2; floats that left this region at the northern or eastern border were not considered as part of the ensemble. An analysis of the deep water not exported at 32°N is beyond the scope of this paper.)

[9] The Lagrangian trajectories of floats that do make it into the subtropical gyre (Figure 2) reveal a first major eastward branching north of Flemish Cap and further diversions out of the western boundary current east of the Grand Banks. While 90% of the floats that eventually arrive at the western boundary in the subtropics follow the continental slope with the DWBC (Table 1), 10% follow eastern pathways along the Mid-Atlantic Ridge (MAR) until they finally turn westward south of 38°N. Closer inspection of individual paths reveals that this deflection is related to the quasi-stationary eddies (in this 12 month average) adjacent to the shelf topography of the Grand Banks.

4. Lagrangian Paths in the Eddying Field

[10] To take the synoptic variability in the model's velocity fields explicitly into account, 24 ensembles of

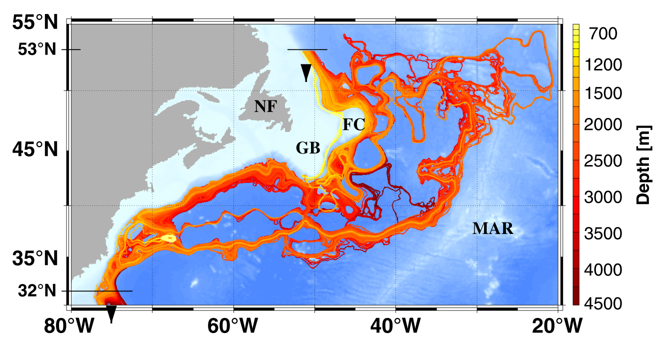

Figure 2. Illustration of deep water pathways showing the trajectories of Lagrangian packages marked at 53°N which, moving with a time mean, 3d-flow field, eventually arrive in the DWBC at 32°N (i.e., 1013 out of 6500). Note that with the actual, time-varying flow field, additional interior pathways due to diversion from the DWBC along the Grand Banks occurs. Color of trajectories indicates depth of the floats. FC: Flemish Cap; GB: Grand Banks; NF: Newfoundland; MAR: Mid-Atlantic Ridge.

Table 1. Relative Contributions of Lagrangian Floats Marked at 53°N to the Main Export Paths Across 43°N in the Time-Mean and Time-Dependent Experiments[a]

Experiment	DWBC	Interior	MAR
Time-mean	90	0	10
Time-dependent	60	30	10

[a]Contribution given as percent. Routes comprise "direct" route along the DWBC, eastern route along the MAR, and irregular pathways through the basin interior.

about 750 Lagrangian floats each were computed using daily velocity fields with fortnightly starting times. Again, the floats were seeded across the DWBC at 53°N from 700 m depth to the bottom. Now, about 30% of the exported waters are deflected off the DWBC to follow irregular paths in the interior of the Newfoundland basin between the DWBC regime and the path along the MAR (Table 1). In spite of this eddy-related detrainment, 60% of the Lagrangian floats that arrive at 32°N still round the Grand Banks in a continuous DWBC, in agreement with inferences based on tracer distributions as discussed by, for example, *Smethie et al* [2000]. (Note, however, that this constitutes only 10% of the total of the original packages seeded at 53°N.) In several case studies, floats were seeded into the DWBC at times when intense eddies were close by. In this way, it was possible to visualize how part of the DWBC transport is deflected into the interior by individual eddies (not shown). This supports the hypothesis by *Fischer and Schott* [2002] of a lateral exchange between DWBC and NAC by eddy stirring. An analysis of data from isopycnal RAFOS floats [*Dutkiewicz et al.*, 2001] demonstrated the same process.

[11] However, if a significant portion of the water in the model is still able to remain in the DWBC, why then do floats in observational programs not follow this path at all?

5. Effects of Float Properties

[12] To shed more light on this, the following analyses are restricted to the LSW layer of the model, with floats now seeded at 43°N (Figures 1a and 1c) to eliminate the effect of dispersion before reaching the tip of the Grand Banks. Using the time-mean flow field, 710 Lagrangian

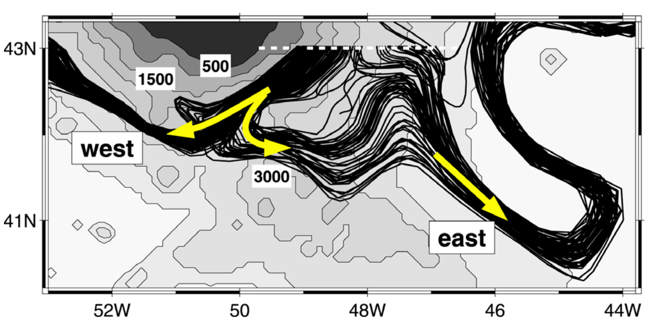

Figure 3. Bifurcation into western and eastern paths near the tip of the Grand Banks, illustrated by Lagrangian trajectories started at 43°N between 1200 m and 2000 m, subjected to the time-mean velocity field.

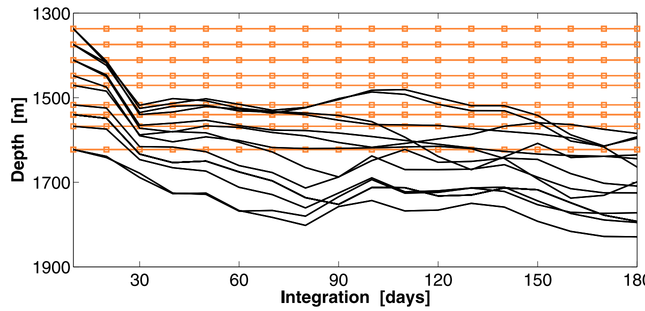

Figure 4. Depth as function of time after release of two sets of floats at 43°N (black: Lagrangian; orange: isobaric) negotiating the tip of the Grand Banks.

floats are initialized between 1200 m and 2000 m depth. This initial float distribution demonstrates a bifurcation of the pathways south of the tip of the Grand Banks (Figure 3), with 58% of these floats following the DWBC and 42% turning eastward with the northern flank of the NAC before finally turning south at the western side of the MAR.

[13] To study the effect of the different characteristics of floats used in observational programs (RAFOS, PALACE or SOLO [see *Davis and Zenk*, 2001]), float characteristics were now defined as "isobaric" (i.e., using the horizontal velocity field on constant geopotentials) in contrast to the "Lagrangian" computations shown above. This results in an increased diversion onto the eastern path (59%). An analysis of the vertical displacements of these floats (Figure 4) shows that almost immediately within the first 30 days after release, i.e., in the approach to the tip of the banks, the water mass descends by about 100–300 m with the 3-dimensional flow field, with a more gradual descent thereafter.

[14] A significant fraction of the isobaric floats left behind at higher levels encounters the eastward flow of the baroclinic NAC (see Figure 1c) upon reaching the southern tip of the Grand Banks, and is thus forced to recirculate with the NAC. The deep floats, on the other hand, are able to continue west underneath the NAC with the DWBC.

[15] To simulate the effect of a periodic surfacing of floats, "profiling" floats were defined by transferring isobaric floats instantaneously to the surface every 10 days with either a surface time of 12 hours [*Fischer and Schott*, 2002] or only 2 hours. This demonstrates that the situation at the tip of the Grand Banks is further aggravated if the floats intermittently follow the surface currents. Table 2 shows the effect in comparison to the isobaric floats: all of the profiling floats leave the DWBC when they enter the region where the NAC's surface velocity field is able to carry them to the east. However, the rate of diversion by the NAC critically depends on the surfacing interval: an

Table 2. Percentage of Floats Started at 43°N and Diverted to the Western (DWBC) and Eastern (MAR) Export Path for Different Float Characteristics

	Lagrangian Floats	Isobaric Floats	Profiling Floats	
			12 Hours	2 Hours
DWBC	42	59	100	66
MAR	58	41	0	34

experiment with reduced surface time (Table 2) almost recovers the isobaric floats' behavior.

6. Conclusions

[16] The Lagrangian model analysis highlights the crucial role of the DWBC's interaction with the intense eddy activity associated with the NAC, particularly near the southern tip of the Grand Banks: This area thus appears not only as a "crossroad" for the upper, northward branch of the MOC [*Rossby*, 1996], but also for the southward transport of deep water. The model supports the view deduced from hydrographical observations that part of the export of LSW from the Labrador Basin to the subtropical North Atlantic takes place on routes both in the interior of the Newfoundland Basin and along the MAR. In the model, even if particles are seeded immediately north of the critical "corner", a large fraction (42%) is still diverted from the DWBC. Yet, observations suggest that EKE observed in that region may even be somewhat higher than in the model, implying that the real detrainment rate may be slightly underestimated.

[17] The present analysis focused on the float behavior in this region, indicating that observational tools that are not fully Lagrangian are likely to encounter intrinsic problems in following the water masses. However, the study also suggests that the eddy-related exchange mechanisms described here should be at work along the whole DWBC, preventing individual water parcels from remaining in a continuous DWBC for long distances. In the present simulation, only 10% of the original water parcels tagged at 53°N were transported to 32°N via the DWBC, although Eulerian depictions indicate a strong mean DWBC along its whole path. This finding implies that our perception of a "continuous current" should be treated with caution. Even in case of a coherent current signature in a succession of sections, the water actually transported is constantly exchanged with the interior.

[18] **Acknowledgments.** We gratefully acknowledge the contribution by Lars Czeschel in running the high-resolution model at DKRZ, Hamburg. Also we kindly acknowledge the helpful discussions with Susan Lozier, Amy Bower, Dagmar Kieke and Fritz Schott on the interpretation of model and float results. This is a contribution of Sonderforschungsbereich (SFB) 460, Kiel University.

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